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THE OSCILLATION METHOD OF X-RAY ANALYSIS OF CRYSTALS

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ABSTRACT

In the oscillation method of crystal analysis a crystal is mounted on an axis and turned back and forth through an angle of about 30° from preferably a known position. A beam of monochromatic X-rays normal to the axis of rotation strikes the crystal and is diffracted. The spectra are recorded on a photographic plate. The coordinates for each spot or spectrum are measured. These data are used for the construction of a projection of a new lattice called the reciprocal one with respect to the crystal space lattice. In the projection the indices of each plane producing a spectrum can be read off directly. The advantages of this method especially in the case of crystals with low symmetry are mentioned below. It is also possible to distinguish with it members of groups like that of the feldspars, which is extremely difficult, if possible at all, with the Laue and powder methods.

As comparatively few students will be able to understand the method thoroughly by merely reading this paper, therefore, the application of the method will be described shortly by a detailed example, that of the determination of the space group of analcite. For a proper understanding of this method the student should have a working knowledge of the simplest formulas of spherical trigonometry and of analytical geometry.

INTRODUCTION

Since the discovery of the diffraction of X-rays by crystals in 1912, probably no method of crystal-analysis has promised greater success for the future than the rotation method by Seemann[1] and Polanyi,[2] and the oscillation method by Schiebold.[3] While in the rotation method the crystal is rotated 360° about an axis, in the oscillation method the crystal is turned back and forth about an axis through a limited number of degrees (usually 30).

Since this method has been described but briefly[4] in America, and only one paper of any length has appeared in English[5] an explanation and discussion of the method with one or two detailed examples may be of value.

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[1] Seemann, H.; *Phys. Zeitschr.*, vol. **20**, p. 169 (1919).

[2] Polanyi, M.; *Die Naturwissenschaften*, vol. **9**, p. 337 (1921).

[3] Schiebold, E.; *Fortschritte der Mineralogie, Krist. und Petrog.*, vol. **11**, pp. 113–280 (1927).

[4] Wyckoff, R. W. G.; The structure of crystals, *New York* (1924).

[5] Bernal, J. D.; *Proc. Royal Soc. London*, vol. **113A**, p. 116.

For the following reasons the oscillation method can be used to great advantage where single crystals, though they may be small, are available: (1) The lengths of the edges of the unit cell of a crystal, as well as the number of molecules in it, can be determined with great precision, regardless of the system of crystallization. Neither the powder nor the Laue method can give us this information in crystals of low symmetry. (2) If the crystal is oscillated in a sufficient number of directions the space group can be determined reliably. The Laue method and, where the symmetry is lower than hexagonal, the powder method, are not to be depended upon for this information. (3) There are often sufficient X-ray

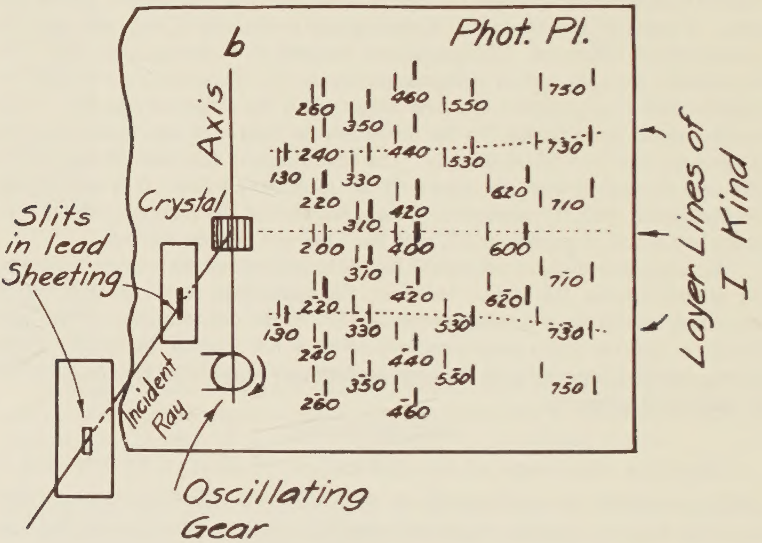

Figure 1

The relation of the crystal mounted on the axis of rotation with respect to the spectra produced on the photographic plate. The spectrogram is that of adularia oscillated about the crystallographic *b* axis. Each spectrum is represented by a *pair* of short lines. The line nearer the axis is the β, the one farther away the α line of the *K* radiation of molybdenum. Usually only the α line is used. Some of the layer lines of *I* kind (hyperbolas) are indicated by dotted lines. Layer lines of *II* kind, parallel to the axis, are sufficiently prominent to be seen without further indications. The widths of the lines of the spectra in the diagram are supposed to show intensity of reflection. (After Schiebold.)

spectra recorded on the plates to make important deductions as to parameters of the structure. At present the Laue method is the one most widely used for this purpose.

Bragg's[6] ionization method is and will of course continue to be of great importance in special investigations, but ordinarily it would require much more time than could be given to a problem.

It is not intended to give descriptions of apparatus and the technique necessary for the application of the method, but an explanation of the principles and especially of the graphical methods used in the interpretation of spectrograms. This the writer studied at the Mineralogische Institut at Leipzig under Prof. E. Schiebold and Prof. F. Rinne, to whom he is greatly indebted.

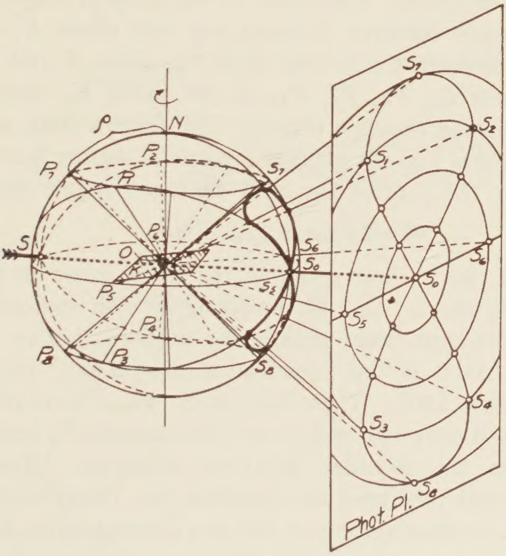

Figure 2. (After Schiebold).

Fig. 1 shows diagrammatically the arrangement of the axis of rotation upon which the crystal is definitely oriented with reference to the incident X-rays. The spectra produced on the photographic plate, which is normal to the incident ray, are shown also. As far as possible the same letters will be used for corresponding points in all the diagrams accompanying this paper.

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[6] Bragg, W. H., and Bragg, W. L.; X-rays and crystal structure. *London* (1925)

GEOMETRICAL RELATIONS IN THE OSCILLATION METHOD

Fig. 2 illustrates how reflection occurs in the rotating crystal method, of which the oscillation method is a special case. SOS_0 is the incident monochromatic X-ray which meets a plane K of a crystal in O, the center of the spherical projection. ON is the axis about which the crystal is rotated. For the sake of convenience we make it normal to the incident ray SOS_0. Points of reflection are recorded on the photographic plate (Phot. Pl.), which is normal to the ray SOS_0. Reflection by the plane K depends on α[6a], the glancing angle between incident ray and plane K, and upon ρ, the angle between the normal upon the plane K and the axis ON. The normals P_1, P_2, P_3, P_4, to the plane K, when at various positions during rotation through 360° form a conic surface whose vertex angle is 2 ρ. In general a plane K during a complete rotation about ON fulfills the well known Bragg's equation,[7]

$$n\lambda = 2d \sin \alpha, \text{ four times.} \qquad (1)$$

This gives rise to four spots of the same order on the plate, for example S_1, S_2, S_3, S_4. If the plane K with indices *hkl* happens to be in the zone [*uvw*] parallel by construction to the axis ON, ($hu+kv+lw=0$ is the equation of the plane),[8] the vertex angle of the cone is 180°. Therefore, each two of four reflections will coincide and only two will occur (for example S_5, and S_6). These two lie in the so-called principal spectrum (*Hauptspektrum*). Other special positions are possible but improbable.[9]

For the understanding of the angular relations and the interpretation of the spots on the photographic plate Fig. 3 has been drawn. AN is the axis of rotation, SAO^1 is the incident ray which lies in the plane of the principal meridian SNO. SA is normal to AN and the photographic plate (Phot. Pl.). K is the plane of reflection. AP is normal to it. AR is the reflected ray which meets the plate at R^1. ρ_P is the angle NP between the normal to the plane K and the axis AN. $\rho_R = NR$ is the angle between the reflected ray and the axis AN. ϕ[9a] is the angle OQ_P in the equatorial plane, or in other words the meridian angle of the pole P. $\phi_R = OQ$ is the meridian angle of the pole R. $\bar{\phi} = NSP = Z^1O^1R^1$ is the angle between the great circle $SPRO$ and the principal meridian. The coordinate system x, z on the plate is right-angled. $\bar{\phi}$ and $\bar{r}$ are the polar coordinates of R^1. The points O and O^1 could have been made to coincide except for the sake of clearness of the drawing. $r = AO^1$ is the distance of the plane K to the photographic plate.

[6a] α is called Θ by the Braggs. The reader is referred to pp. 6–15 and 73–103 of their elementary book (*op. cit.*).

[7] *Op. cit.*, p. 13.

[8] See for example: Dana's Textbook of Mineralogy, 3d ed., p. 46 (1922).

[9] Schiebold, *op. cit.*, p. 119.

[9a] The greek letter ϕ in the drawings looks slightly different from the printed one.

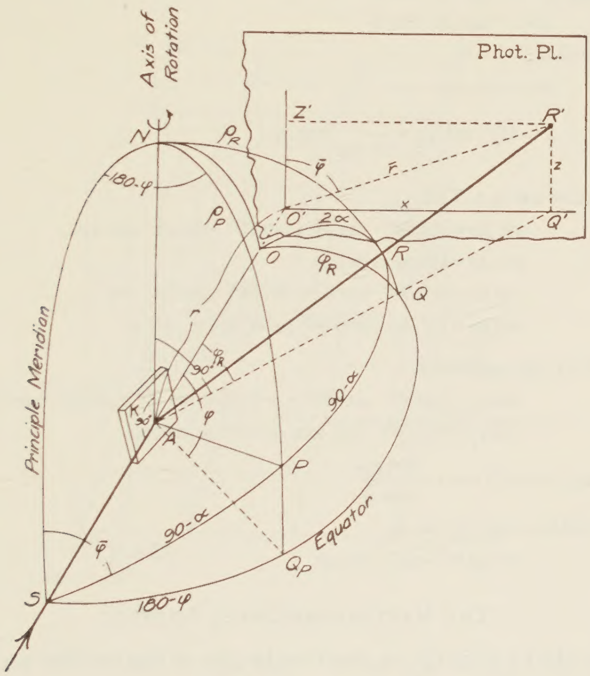

Figure 3.

It is obvious that $OR = 2\alpha$ when reflection occurs (see equation (1)). Since AP is normal to K, $SP = 90° - \alpha$ and $PR = 90° - \alpha$. In Δ SPN by the sine law,

$$\frac{\sin(90° - \alpha)}{\sin(180° - \phi)} = \frac{\sin \rho_P}{\sin \bar{\phi}} = \frac{\cos \alpha}{\sin \phi}.$$

By the cosine law,

$$\cos(90° - \alpha) = \cos 90° \cdot \cos \rho_P + \sin 90° \cdot \sin \rho_P \cdot \cos(180° - \phi) \text{ or, } \sin \alpha = \sin \rho_P \cdot \cos(180° - \phi) \qquad (2)$$

Suppose x and y or $\bar{r}$ and $\bar{\phi}$ to be given:

$$\bar{r}=r \cdot \tan 2\alpha$$

$$\frac{\bar{r}}{r}=\tan 2\alpha$$

$$x=\bar{r}, \sin \bar{\phi}$$

$$z=\bar{r} \cdot \cos \bar{\phi}$$

Substituting, $x=r \cdot \tan 2\alpha \cdot \sin \bar{\phi}$

$$z=r \cdot \tan 2\alpha \cdot \cos \bar{\phi}$$

By construction,

$$x=r \cdot \tan \phi_R$$

$$z=AQ' \cdot \cot \rho_R=\frac{r}{\cos \phi_R} \cdot \cot \rho_R \qquad (4)$$

By the cosinel aw in $\Delta\, NRO$,

$$\cos 2\alpha=\cos 90° \cdot \cos \rho_R+\sin 90° \cdot \sin \rho_R \cdot \cos \phi_R$$

or, $\cos 2\alpha=\sin \rho_R \cdot \cos \phi_R$

and, $\cos \rho_R=\cos 90° \cdot \cos 2\alpha+\sin 90° \cdot \sin 2\alpha \cdot \cos \bar{\phi} \qquad (5)$

or $\cos \rho_R=\sin 2\alpha \cdot \cos \bar{\phi}=2 \sin \alpha \cdot \cos \alpha \cdot \cos \bar{\phi} \qquad (6)$

In $\Delta\, NPO$ by the cosine law,

$$\cos \rho_p=\cos 90° \cdot \cos(90°-\alpha+2\alpha)+\sin 90° \cdot \sin(90°-\alpha+2\alpha) \cdot \cos \bar{\phi}$$

or, $\cos \rho_p=\sin (90°+\alpha) \cdot \cos \bar{\phi}=\cos \alpha \cdot \cos \bar{\phi} \qquad (7$

Substituting from (7) $\cos \alpha=\dfrac{\cos \rho_P}{\cos \bar{\phi}}$

we have another form for $\cos \rho_R$,

$$\cos \rho_R=2 \sin \alpha \cdot \cos \rho_P \qquad (8)$$

THE RECIPROCAL SPACE LATTICE

It would be difficult to explain the use of the oscillation method especially the graphical interpretations without introducing the conception of the reciprocal lattice, used first by Ewald.[10]

If we consider a crystal as a simple space lattice we may choose three directions or vectors $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, in it as primitive translations, (Fig. 4). These may serve also as axes[11] when they will be marked

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[10] *Zeitschr. f. Kristallographie*, vol. 56, p. 129 (1921).

[11] It is customary to use German letters for vectors or directed magnitudes and corresponding Latin ones for absolute lengths. In Fig. 4, then, $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, imply not only the lengths of the edges of the parallelopiped but also their directions. a, b, c, on the other hand, are used either just for the lengths of the edges or to designate the three crystallographic axes. A primitive translation is the vector from an atom to the nearest identical atom in the direction of the vector. See f. example Wyckoff, R. W. G., *op. cit.*, pp. 56–58.

a, b, c to distinguish them from the translations 𝔞, 𝔟, 𝔠. A plane in such a lattice may be designated by Miller indices *h, k, l,* where the intercepts of such a plane are *a/h, b/k, c/l,* on *a, b, c,* respectively.

The origin of the unit cell or parallelopiped is at 0. The planes which have as indices integers prime to each other are farthest away from the origin in the cell. They are responsible for the *I* order reflections. Planes which are sub-multiple distances of the first mentioned planes away from the origin have indices that are multiples of the indices consisting of integers prime to each other. These intermediate planes produce the higher orders of reflection.[12] In Fig. 4, considering the pinacoid, for example, plane (100) would be farthest away from the origin in the unit cell *OAFBCHDG,* and would produce *I* order reflections. The plane (200) would be half way between and would cause *II* order reflections and so forth.

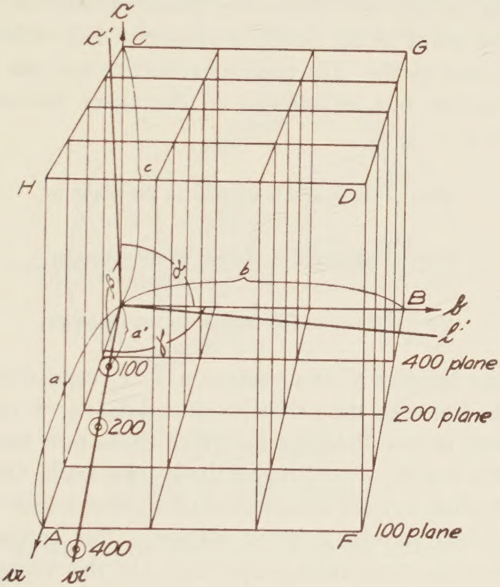

Figure 4.

"Now from the planes of the lattice, as so defined (quoting Bernal[13]) another lattice can be built up each point of which lies on the normal from the origin to a plane and at a distance h[14] from the origin, h and the spacing d of the plane being related by

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[12] Bragg, op. cit., p. 13.

[13] *Op. cit.,* p. 118.

$$hd=k^2 \tag{9}$$

where k is a constant. In other words, each point in the new lattice is the reciprocal polar of a plane in the old lattice in a sphere of radius k." The new lattice is called the reciprocal lattice (reziprokes Gitter) of the old. For every plane in one may be found a corresponding point in the other as shown in Fig. 4 for the planes (100), (200), and (400). The reciprocal lattice has the same origin as the old lattice but is referred to the three vectors $\mathfrak{a}^1$, $\mathfrak{b}^1$, $\mathfrak{c}^1$. With respect to $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$,[15]

$$\mathfrak{a}^1=\frac{k^2bc}{V}\sin\alpha, \text{ and is normal to the plane } \mathfrak{bc},$$

$$\mathfrak{b}^1=\frac{k^2ca}{V}\sin\beta, \text{ and is normal to the plane } \mathfrak{ca},$$

$$\mathfrak{c}^1=\frac{k^2ab}{V}\sin\gamma, \text{ and is normal to the plane } \mathfrak{ab},$$

a, b, c are the lengths of the vectors $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$ respectively, α, β, γ, are the angles between the primitive translations. V is the volume of the unit cell or parallelopiped. With these new vectors $\mathfrak{a}^1$, $\mathfrak{b}^1$, $\mathfrak{c}^1$ whose lengths are a^1, b^1, c^1, respectively, we build the reciprocal lattice in which h, k, l are the indices of a point which corresponds to a plane (hkl) in the original lattice. The reciprocal lattice has the following important properties: (1) the vector $\mathfrak{h}$ (Fig. 6) to a point P_{hkl} of the reciprocal lattice is the normal to the corresponding plane (hkl) of the space lattice. (2) The length h of the vector $\mathfrak{h}$ to the first point encountered in a given direction in the reciprocal lattice is equal to $1/d_{(hkl)}$. d is the distance between equivalent planes in the space lattice. (3) The coordinates of a point P_{hkl} in the reciprocal lattice are proportional to the indices of the corresponding plane (hkl) in the space lattice, or in other words if x^1, y^1, z^1 are the coordinates, $x^1=a^1h$, $y^1=b^1k$, $z^1=c^1l$. (4) The volumes of the unit cells of the two lattices are reciprocal to each other $V=1/V^1$. V^1 is the volume of the unit of the reciprocal lattice.

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[14] I substituted h for Bernal's ρ because ρ is used for angles in my paper. This h has no relation to the index h, but is the length of the vector $\mathfrak{h}$ used further on. d is always the spacing between equivalent planes.

[15] Ewald, *op. cit.*

Bernal says,[16] "It is difficult to obtain a physical picture of the phenomena in the reciprocal lattice corresponding to the diffraction of X-rays in crystals. By assuming Bragg's law, however, we can obtain a geometrical one." If the angle between the incident ray and the reflecting plane in the space lattice satisfies the equation (1) reflection occurs. In the reciprocal lattice α is the angle between the incident ray and the plane which is normal to the radius vector $\mathfrak{h}$ connecting the origin O with the point P_{hkl} which

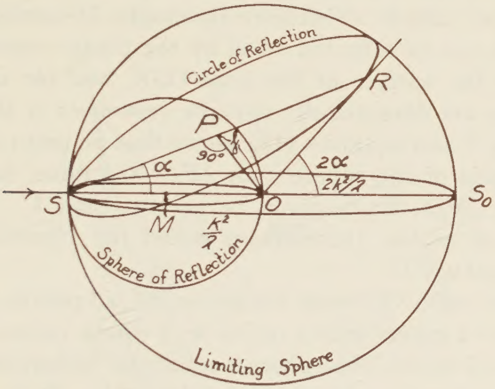

Figure 5. (After Bernal.)

corresponds to the plane (hkl) in the space lattice. (See Fig. 5.) By equation (9)

$$h=\frac{k^2}{d} \text{ or, } d=\frac{k^2}{h} \tag{10}$$

Substituting (10) in equation (1), we get (assuming for the present $n=1$)

$$\sin\alpha=\frac{\lambda h}{2k^2} \tag{11}$$

Fig. 5 (after Bernal) is an attempt to present reflection in the reciprocal lattice diagrammatically. SOS_0 is the incident ray. A sphere with a radius $2k^2/\lambda$ is drawn around O as center. The point P in the sphere is the point of the reciprocal lattice corresponding to the reflecting plane of the space lattice. OP is the radius vector $\mathfrak{h}$ which is normal at P to a plane SR which cuts the sphere in the circle marked "circle of reflection." *SPR* is a straight line in that plane. Then

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[16] *op. cit.* p. 120.

$$\sin OSP=\frac{h}{\frac{2k^2}{\lambda}}=\frac{\lambda h}{2k^2} \text{ which is equation (11) Bragg's equation.}$$

h is the length of the vector $\mathfrak{h}$ in this equation.

The incident ray SO, therefore, will be reflected along OR by a plane in the space lattice which corresponds to the point P in the reciprocal lattice. Therefore the angle $ROS_0=2\alpha$. Further all rays that can be reflected at all by the plane corresponding to P lie along the surface of the cone OSR, *and the incident and reflected rays are diametrically opposite generators of this cone.* A study of Fig. 5 and equation (11) shows that no point of reflection can lie outside of the sphere with $2k^2/\lambda$ as radius, for if h were longer than $2k^2/\lambda$, $\sin\alpha$ would be greater than 1. The sphere with $2k^2/\lambda$ as radius, therefore, is called the "limiting sphere," (Begrenzungskugel).

Since the angle SPO must always be 90°, all points P will lie on the surface of a sphere with a radius k^2/λ whose center M lies half way between S and O. This sphere is called the "sphere of reflection" (Ausbreitungskugel by Ewald and Schiebold). It is exceedingly useful in finding the indices of the spots in the photograph, for only those planes can reflect whose points P in the process of rotation about O *pass through the surface* of the sphere of reflection. Therefore the number of reflections is limited by the angle of rotation or oscillation, respectively.

THE EVALUATION OF REFLECTIONS IN THE PHOTOGRAMS

The plotting of reflections and the determination of their indices resemble the gnomonic projection. (See Fig. 11.) If in equation (9) we choose $k=1$ we have

$$h_{hkl}\cdot d_{hkl}=1, \text{ or } h_{hkl}=\frac{1}{d_{hkl}}.$$

$d_{hkl}=$ the distance between equivalent planes (hkl). In order to find h_{hkl}, the length of vector $\mathfrak{h}_{hkl}$, we construct the auxiliary figure 7. With two arbitrary lengths a^1, b^1, we draw a reciprocal lattice in two dimensions. With the radius $k_2/\lambda=1/\lambda$ (λ here is also arbitrary) we draw the circle marked "sphere of reflection in

Fig. 5, so that O will lie on its surface. Any other point P_{hkl}, of the lattice that happens to be on the surface is a possible point of reflection. $OP_{hkl}=h_{hkl}$, therefore. Since OMP is an isosceles triangle, the normal from M upon OP bisects the angle $2\alpha=OMP$.[16a]

$$OL=PL=OM\cdot\sin\alpha$$

therefore, $\frac{1}{2}h=1/\lambda\cdot\sin\alpha$, and since $h_{hkl}=1/d_{hkl}$

$$h_{hkl}=\frac{1}{d_{hkl}}=\frac{2}{\lambda}\sin\alpha_{hkl} \tag{12}$$

which is equation (1) in a slightly different form.

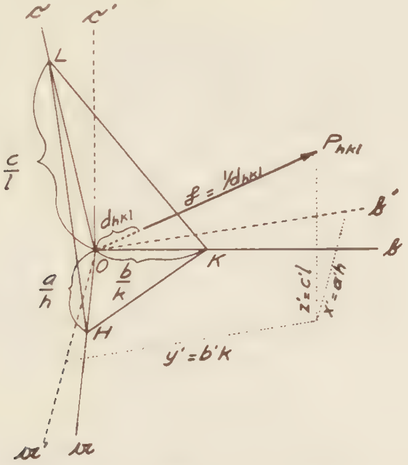

Figure 6

Axial relations of space lattice to reciprocal lattice. $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$ are primitive translations and axes of space lattice. $\mathfrak{a}^1$, $\mathfrak{b}^1$, $\mathfrak{c}^1$ are primitive translations of reciprocal lattice. $\mathfrak{a}^1$ normal to plane $\mathfrak{b}\mathfrak{c}$, $\mathfrak{b}^1$ normal to plane $\mathfrak{c}\mathfrak{a}$, $\mathfrak{c}^1$ normal to plane $\mathfrak{a}\mathfrak{b}$.

But the length of $\mathfrak{h}$ is one of our polar coordinates in the reciprocal lattice corresponding to $\bar{r}$ on the spectrogram of the space lattice (Fig. 3), as will be seen more clearly in Fig. 11. For plotting the length of $\mathfrak{h}$ we need a factor which will make our projections of a convenient size. We choose $R_0\lambda/2$ ($Ro=500$ mm. usually is convenient). Multiplying both sides of equation (12) by this factor $R_0\lambda/2$ we get

$$\frac{R_0\lambda}{2d_{hkl}}=Ro\cdot\sin\alpha_{hkl}. \tag{13}$$

[16a] The incident ray is parallel to MO and not as shown in Fig. 7.

The radius of the sphere of reflection $1/\lambda$ when multiplied by the same factor becomes $Ro/2$, or 250 mm. if we choose $Ro=500$ mm. To locate a point P_{hkl} in the projection of the reciprocal lattice corresponding to a plane (hkl) we use the polar coordinates $Ro\cdot\sin\alpha_{hkl}$ and $\rho_{P_{hkl}}$ which we compute with the aid of equation (7).

An examination of the spots in a photogram taken by the oscillation method (for example Fig. 1) shows that they are arranged in distinct lines or curves at right angles to the trace of the axis of rotation provided the axis is parallel to a prominent crystallographic direction. These lines or curves are called "layer lines of I kind" (Schichtlinien I. Art). In order to explain these lines we go back to the conception of the one dimensional lattice by Ewald.[17] We *imagine* the space lattice to be made up of three one-dimensional ones. Each of them is parallel to one of the primitive translations $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$. A one-dimensional lattice consists of a line on which atomic centers are spaced at equal intervals. We orient the lattice so that the one-dimensional one parallel to $\mathfrak{c}$ is also parallel to the axis of rotation. In Fig. 8 the one-dimensional lattice with the direction $[u_3v_3w_3]$ of the c axis and of the axis of rotation is shown. (Any other direction or line on which atoms occur at regular intervals could have been chosen.) Neighboring atomic centers A_0, A_1 are a primitive translation $T_{[u_3v_3w_3]}$ apart.

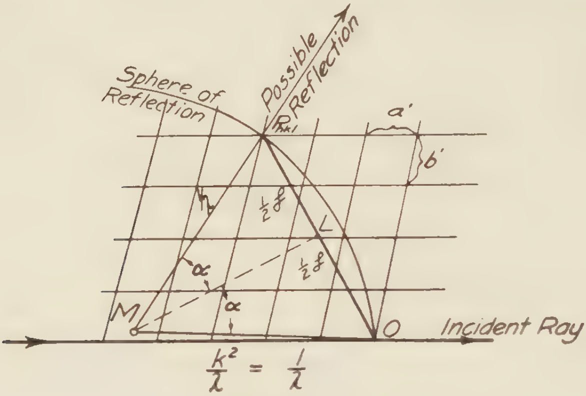

Figure 7.[16a]

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[17] Ewald, P. P., Kristalle und Röntgenstrahlen, *Berlin*, **1923**, p. 42.

The parallel beam of monochromatic rays S_1S_2 meets the lattice and is diffracted. Since each atom sends out spherical wave impulses[18] the diffracted beams lie on a cone whose vertex angle is equal to 2γ. The axis of the cone is the line $[u_3v_3w_3]$ as shown in Figs. 8 and 9. Diffraction (or reflection) occurs only in those directions where the phase difference between impulses from adjacent atoms is an integral multiple of the wave length λ. In other words, in Fig. 8

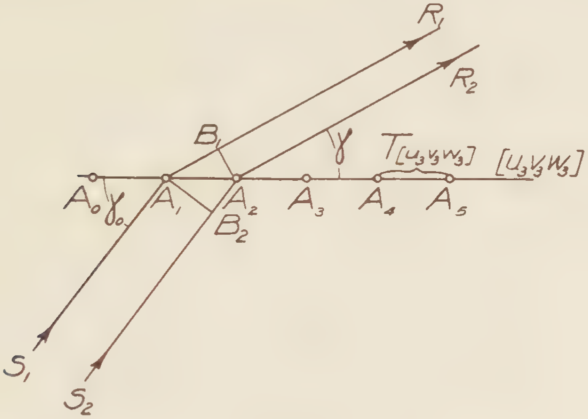

Figure 8.

$$A_1B_1 - A_2B_2 = 0,\ 1,\ 2,\ 3,\ \cdots,\ l'\lambda$$

$$A_1B_1 = T_{u_3v_3w_3} \cdot \cos\gamma$$

$$A_2B_2 = T_{u_3v_3w_3} \cdot \cos\gamma_0$$

$$A_1B_1 - A_2B_2 = l'\lambda = T_{u_3v_3w_3} \cdot (\cos\gamma - \cos\gamma_0) \qquad (14)$$

This equation and two other exactly similar ones to be mentioned later are called the Laue equations. l' is the order of reflection in the one dimensional lattice just as n is the order in the three dimensional lattice in equation (1).

In Fig. 9 we assume a special case, that of the incident ray S being normal to the axis of rotation which is parallel to a prominent crystallographic direction. The cones of reflection of the different orders cut the photographic plate in hyperbolas. The O order will be a special case, namely a straight line. In the figure we must imagine the cones to extend also downward from the O order. All spots, therefore, have these hyperbolas or layer lines for one of their loci. They become straight lines normal to the axis of rotation in the projection of the reciprocal lattice. Figs. 3 and 8 show that the angle ρ_R and γ are identical. Since we are dealing with an incident ray *normal* to the direction $[u_3v_3w_3]$ the cosine of γ_0 becomes 0. We may substitute in (14) ρ_R and get

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[18] These spherical waves can be explained by Huygens' principle. Only waves which are exactly in phase lie on the surface of the cone.

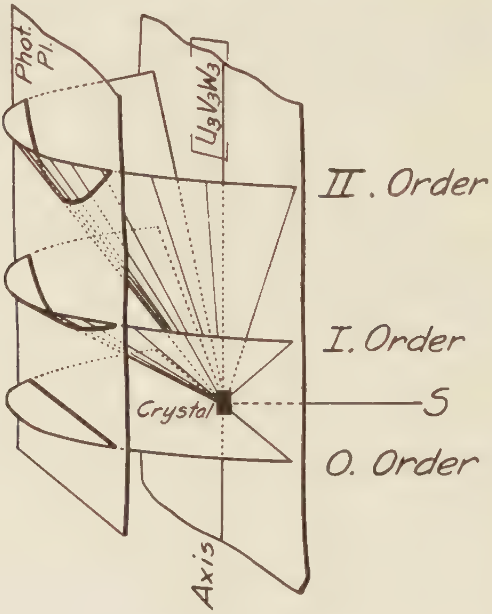

Figure 9. (After Ewald.)

$$l'\lambda = T_{u_3v_3w_3}\cdot\cos\rho_R \tag{14'}$$

By equation (6) and (8) $\cos\rho_R = \sin 2\alpha\cdot\cos\phi = 2\sin\alpha\cdot\cos\rho_P$. Substituting in (14′) we get

$$\sin 2\alpha\cdot\cos\overline{\phi} = 2\sin\alpha\cdot\cos\rho_P = \frac{l'\lambda}{T_{u_3v_3w}}$$

$$= \text{a constant for each layer line} \tag{15}$$

Equation 15 may be used for calculating the primitive translation $T_{u_3v_3w_3}$ by taking the mean value of $T_{u_3v_3w_3}$ calculated from all the spots in the photograph. A shorter and more accurate way is to use the reflections of the principal spectrum along the 0 layer line, if we know the orientation of the crystal with respect to the principal meridian and to the incident ray. The principal spectrum consists of reflections from the faces that lie in the zone of the axis of rotation. Therefore it is at right angles to the direction of the axis (See Fig. 1) and to $[u_3v_3w_3]$ which by construction is parallel to the axis. The advantage of taking a prominent crystallographic zone or direction for the axis of rotation is obvious now, for it insures prominent reflections in the principal spectrum. These can be evaluated by equation (1) if we know the approximate T from equation (15), as will be shown in a paper on the structure of analcite. l' in (14) and (15) is an integer. It tells us how many times we must take the distance $T_{u_3v_3w_3}$ in the direction $[u_3v_3w_3]$ to arrive at a certain point. It is the index along $[u_3v_3w_3]$. l' must remain a constant for each layer line as is obvious from equation (14) and (15). (Note the resemblance to the gnomonic projection in this respect.)

Layer lines in the general direction of the axis of rotation (Fig. 1) also appear, if prominent crystallographic planes are normal to the axis. A prominent zone will then be at right angles to the axis. The reflections of such a zone lie on a curve which is almost a straight line near the principal spectrum. All the points in the reciprocal lattice corresponding to the planes in such a zone lie in a plane. Therefore, these layer lines are straight lines in the reciprocal lattice. Schiebold calls them layer lines of *II* kind. Only the index referring to the coordinate in the direction of the axis of rotation changes along these lines as shown later.

In order to make our evaluation quite general regardless of which prominent crystallographic direction is the axis of rotation we look at the portion of (15) $l'\lambda/T_{u_3v_3w_3}$. On each layer line of *I* kind the index l' is a constant. If the direction parallel to the axis of rotation is not one of the primitive translations $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, but some other crystallographic direction, we employ the well known transformation formulas to find the indices with respect to the primitive translation $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$.

$$h' = hu_1 + kv_1 + lw_1$$

$$k' = hu_2 + kv_2 + lw_2$$

$$l' = hu_3 + kv_3 + lw$$

In these equations $[u_1v_1w_1] = \bar{\mathfrak{a}}$

$[u_2v_2w_2] = \bar{\mathfrak{b}}$

$|u_3v_3w_3] = \mathfrak{c}$

$\bar{\mathfrak{a}}$, $\bar{\mathfrak{b}}$, $\bar{\mathfrak{c}}$ are the three primitive directions or axes of a new orientation of the lattice with reference to the crystal axes a, b, c. $\bar{\mathfrak{c}}$ is the axis of rotation. h', k', l' are the indices with reference to the directions $\bar{\mathfrak{a}}$, $\bar{\mathfrak{b}}$, $\bar{\mathfrak{c}}$. h, k, l are the indices with reference to the crystal axes a, b, c, (or in other words with reference to the primitive translations $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$ of the unit cell). For every layer line of *I* kind we get the equation:

$$l' = s = hu + kv + lw = 0, \pm 1, \pm 2, \cdots \pm \text{ integer}$$

$[uvw]$ are the indices of the axis of rotation, and (hkl) the indices of the reflecting plane both with reference to the crystal axes a, b, c. s I propose to call the index of summation (Aufzählungsindex). This equation *must* be satisfied, if the indices have been placed correctly.

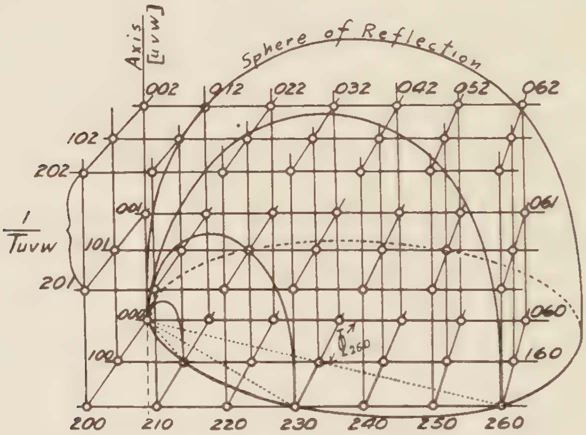

Figure 10

Sphere of reflection penetrating a portion of the reciprocal lattice. For the sake of clearness only some of the points have received indices. The small circle connecting point (000) and point (260) is the limiting circle for the vertical plane in which the two points lie. Its radius is $R_0/2 \cdot \sin \Phi_{260}$.

The layer lines of *II* kind can be explained similarly. The loci for the reflection of the one-dimensional lattice parallel to the axis of rotation are cones as shown in Figs. 7 and 8. The other two primitive directions $\bar{\mathfrak{a}}, [u_1v_1w_1]$ and $\bar{\mathfrak{b}}, [u_2v_2w_2]$ of the space lattice can also be imagined as two one-dimensional lattices with loci which are cone surfaces about these directions. Their equations are then similar to (14):

$$T_{u_1v_1w_1}\cdot(\cos\alpha-\cos\alpha_0)=h'\lambda \tag{16}$$
$$T_{u_2v_2w_2}\cdot(\cos\beta-\cos\beta_0)=k'\lambda \tag{17}$$

The loci of the intersections of these two cones lie on curves of the 4th degree in the photographic plate. The curves are almost straight lines near the center and near the principal spectrum. These layer lines of the *II* kind are straight lines in the reciprocal lattice as mentioned before. Every point on one must according to the transformation formulas satisfy the equations:

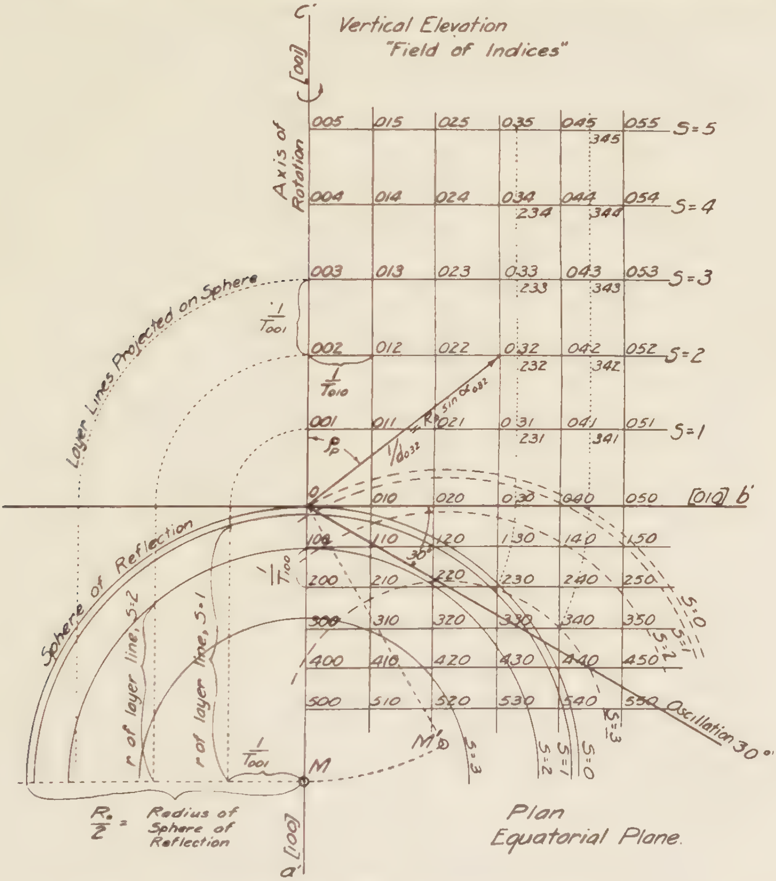

Figure 11.

Vertical elevation and plan of a right angled reciprocal lattice. Only some of the points of the plan have been projected upon the elevation. As an example of how a point is plotted the polar coordinates of point (032) are shown in the vertical projection.

$$h' = hu_1 + kv_1 + lw_1 = \text{constant}$$
$$k' = hu_2 + kv_2 + lw_2 = \text{constant}$$

That means that h' and k' are constant for points that lie on the same layer line of *II* kind. Where these layer lines intersect layer lines of *I* kind all these equations (14), (15) and (17) are satisfied and real reflections are possible at those points. The chances for the surfaces of three cones to intersect in one line are very slight, however, as long as the crystal is not rotating.

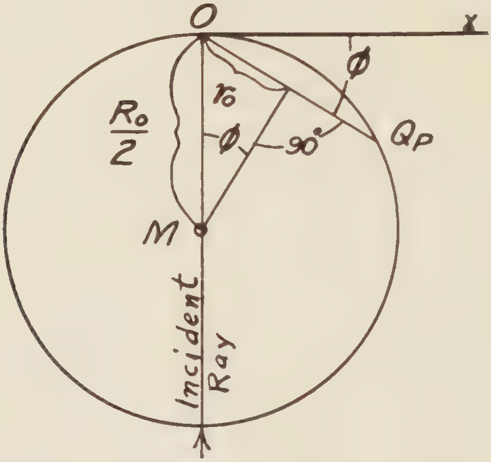

Figure 12.

In Fig. 5 we imagine the limiting sphere filled with the reciprocal lattice. The point of origin of the lattice is at *O*, the center of the sphere. It would be accidental if another point of the reciprocal lattice lay upon the surface of the "sphere of reflection," a condition necessary for reflection. However, if we turn the reciprocal lattice about *O* a definite number of degrees back and forth every point of the reciprocal lattice which passes through the surface of the sphere of reflection will be in position to reflect at that instant. Fig. 10 illustrates how the planes of the reciprocal lattice normal to the axis of rotation cut the sphere of reflection into parallel sections or slices each of which has a thickness of $1/T_{uvw}$ which is the reciprocal of the primitive translation in the direction $[uvw]$ parallel to the axis of rotation. This is also shown in the upper part of Fig. 11 which represents a vertical elevation of the reciprocal lattice parallel to the photographic plate. The lower part of Fig. 11 is the plan of the reciprocal lattice in the equatorial plane. The points in it may be projected upon the elevation as indicated. Schiebold calls this elevation the field of indices (Indicesfeld). Only a small part of the points in the plan need to be projected, however, depending upon the angle of rotation or oscillation respectively. For example, if the angle is 30° no point below the 30° line shown (Fig. 11) is projected, unless it lies within 3° to 4° of the line, for in that case there is a possibility that this point may cause reflection. But this is not the only limitation for points which might be projected. The concentric circles in Fig. 11 represent the surface of the sphere of reflection, each being a distance of $1/T_{uvw}$ above the next larger one. It is obvious that if the reciprocal lattice penetrates the sphere of reflection only through an angle of 30° by rotation about O, only the points in the plan which would go through one or more of the circles during such a rotation need to be projected. An easy way of determining these points is by the aid of a separate drawing of these concentric circles of reflection upon tracing paper. By pinning a point of the equator of the sphere to O in the reciprocal lattice we have a pivot or axis about which we can turn the sphere any desired number of degrees and watch which points of the reciprocal lattice penetrate the circles. In Fig. 11 this operation has been indicated by the dotted circles which represent the position of the sphere of reflection after turning through 30° from the starting position drawn in full lines. There is also a way of limiting the field of indices toward the top of the vertical elevation, Fig. 11. The small circles in Fig. 10 which pass through O, obviously are the lines of intersection of the sphere of reflection with vertical planes of the reciprocal lattice. No point of the lattice outside of the sphere can reflect. If we can draw these small circles on the elevation of Fig. 11, therefore, we eliminate many impossible indices from consideration. The radii of these "limiting circles" (Begrenzungskreise) are $r_0 = R_0/2 \cdot \sin \Phi_{hkl}$. $R_0/2$ is the radius of the sphere of reflection and the angle Φ_{hkl} is the angle which a pole P_{hkl} projected upon the equatorial plane as point Q_P makes with coordinate x, which is normal to the plane of the axis of rotation and the incident ray. The auxiliary construction, Fig. 12 shows how we arrive at this equation for the radii of the limiting circles.

LARSENITE AND CALCIUM-LARSENITE, NEW MEMBERS OF THE CHRYSOLITE GROUP, FROM FRANKLIN, NEW JERSEY. (Preliminary notice)

C. Palache, L. H. Bauer, and H. Berman

The two minerals here to be described were found on the picking table at Franklin by W. H. Ball from whom a considerable supply was secured for the Harvard Mineralogical Museum. The material consists of large blocks of massive ore cut by narrow veins, open in part, and filled or lined by a complex of minerals, including clinohedrite, hodgkinsonite, willemite, roeblingite, hardystonite, garnet, zincite, calcite, bementite, and neotocite. Larsenite is in slender prismatic crystals, the last crystallization in a few cavities; the more abundant calcium-larsenite is for the most part massive, in the walls of the veins or replacing hardystonite in the ore, but is also found imperfectly crystallized in veins. Detailed description of all these minerals will be prepared for later publication. Here it is intended to present briefly the characters of the new mineral.

Larsenite is a lead-zinc orthosilicate with the formula Pb Zn SiO_4 and with crystallographic and optical properties which ally it to the chrysolite group of minerals. The name proposed is in honor of Professor E. S. Larsen of Harvard University.

Calcium-larsenite may be represented by the formula (Pb, Ca) Zn SiO_4, about one-half of the lead of larsenite being replaced by calcium. Its properties are closely allied to those of larsenite.

Larsenite is orthorhombic, generally in slender striated prisms but in a few crystals tabular parallel to *b* (010). The principal forms on the crystals are (010), (012), (110), (142), and (9.8.18); other forms observed are (100), (012), (122), (132), (101), (111), (131). It will be noted that the important pyramids both have complex indices, a fact for which we have no explanation. The form (9.8.18) is very close to the position of (112) but is consistent in its deviation from the simpler form.

The following table shows the rather close relationship of larsenite to the chrysolite group.

	Larsenite	Chrysolite	Tephroite
p_0	1.2268	1.2591	1.2911
q_0	0.5324	0.5865	0.5939
ϕ for prism (120)	49°01′	47°01′	47°23′

Details of crystallographic measurement and calculation will be presented in the later paper.

Larsenite is white and transparent with adamantine lustre. Cleavage is good parallel to the prism (120). Specific gravity 5.90. Biaxial negative, $2V$ about 80°, $\rho > \nu$ easily perceptible. Plane of optical axes across the elongation with an optic axis practically normal to the cleavage (120). Therefore $Y = c$, $X = a$.

$$\alpha = 1.92, \quad \beta = 1.95 \quad \gamma = 1.96, \quad \text{all} \pm .01. \quad \text{(Immersion).}$$

Calcium-larsenite is white and opaque with greasy lustre. No distinct crystals have been found and cleavage is indistinct. Specific gravity 4.421. Under the iron-arc spark it shows a very strong fluorescence of a lemon yellow color, more vivid than that of willemite and easily distinguished from it. The analysis sample is biaxial negative, almost uniaxial, $2\ V = 5°$.

$$\alpha = 1.760, \ \beta = \gamma 1.769, \ \text{all} \ \pm .001$$

A second sample, looking somewhat fresher than the analyzed material, gave $\alpha = 1.762$, $\beta = 1.770$, $\gamma = 1.774$, $2V = 40°$.

The chemical analyses by Bauer are shown below together with the derived formulae.

Analysis of Larsenite

	I	II	III	IV	V	VI
SiO_2	16.87	.281	2.58	15.84	.2641	16.47
PbO	56.66	.254		62.82	.2817	61.20
ZnO	22.74	.279	3.50	21.34	.2621	22.23
FeO	0.10	.001				
MnO	0.14	.002				
CaO	2.42	.043	2.42			
MgO	0.20	.005				
H_2O	0.76	.042	0.76			
Total	99.89		9.26	100.00		100.00

I. Analysis—Larsenite with Clinohedrite impurity.

II. Molecular ratio.

III. Clinohedrite composition using all CaO and H_2O.

IV. Larsenite—remainder after deducting clinohedrite and apparently unessential oxides and reducing to 100%.

V. Molecular ratio.

VI. Larsenite—calculated composition of $PbO \cdot ZnO \cdot SiO_2$.

Analysis of Calcium-larsenite

	I	II		III
SiO_2	24.10	.4017		24.17
FeO	0.48			
MnO	0.57			
CaO	16.36	.293		
ZnO	30.61	.378	.795	75.83
PbO	27.63	.124		
MgO	0.23			
H_2O+110°C	0.12			
	100.10			

I. Analysis—Calcium-larsenite.
II. Molecular ratio.
III. Calculated composition for Mol. wt. of RO=94 or $(PbO+CaO):ZnO:SiO_2$ 1:1:1.

ANAUXITE FROM THE IONE FORMATION OF CALIFORNIA

Victor T. Allen, *University of California.*

Abstract

A mineral having the composition of $5\ H_2O \cdot 2\ Al_2O_3 \cdot 6\ SiO_2$ and for which the name ionite was proposed,[1] forms an important part of the Ione formation of California. Recent work shows that it is probably identical with anauxite from Bilin. Evidence is given which indicates that it is formed from biotite or chlorite by loss of magnesium, calcium, iron, and alkalies and with corresponding increase in water. Chemical analyses and optical data are given. An explanation of the occurrence of rutile in clays is offered.

While mapping the Jackson Quadrangle, H. W. Turner observed a micaceous mineral with pearly luster in the Ione formation. In his paper[2] on the Rocks of the Sierra Nevada he published the following statement regarding it.

> "Very characteristic of the sandstone of the Ione formation are pearly scales of a foliated mineral allied to kaolin. In some cases these scales are colored red by hematite, as in the red sandstone at the quarry southeast of Ione. The mineral under the microscope shows very low polarization colors and seems to extinguish parallel to the basal cleavage lines. Dr. W. F. Hillebrand separated some of this micaceous mineral by means of a heavy solution and made the analysis quoted (No. 1 in Table). A microscopic examination of the material analyzed showed only a few particles of quartz in the field of view. The foliated mineral comprised all the remainder of the material. Perhaps one or two percent might be deducted for the silica of these quartz grains.
>
> "This mineral appears to resemble rectorite[3] in composition but does not show any strong double refraction.
>
> "Professor S. L. Penfield has kindly examined this silicate of aluminum and writes that as it "is not clear and transparent, it is impossible to be sure that it does not contain microscopic quartz or chalcedony silica deposited on it," and is inclined to consider the mineral an impure kaolinite, notwithstanding the high percentage of silica."

The writer's attention was called to this mineral on account of its widespread and uniform occurrence in the Ione clays and sands, which are being used in the manufacture of brick and pottery. It occurs as small books or aggregates with perfect basal cleavage which are usually oriented with the cleavage parallel to the bedding of the rock. The edges of most flakes are irregular, but a few were found which show hexagonal outline and the angle between the faces is approximately 60° and 120°, so that the forms closely resemble those of the micas and certain chlorites. This similarity suggests that the Ione clay mineral also belongs to the monoclinic system. It is biaxial with 2 V variable, equal to 18° in some grains and 32° as a maximum in others. It is optically negative, X is the acute bisectrix, which is very nearly normal to the (001) cleavage. Some crystals are elongated parallel to (010), the plane of symmetry, and the axial plane is parallel to that direction. The dispersion is slight, $\rho > v$. The indices of refraction were determined by the immersion method with the following results, which are the average of several determinations:

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[1] *The American Mineralogist*, Vol. **12**, p. 78, March, 1927.

[2] H. W. Turner. Rocks of the Sierra Nevada. *14th Annual Rept., U. S. G. S* pt. II, **1892**, p. 464.

[3] *Am. J. Sc.*, 3rd Series, Vol. **XLII**, p. 11, 1891.

$\alpha = 1.559$, $\beta = 1.564$, $\gamma = 1.564$; $\gamma - \alpha = .005$. The value for the birefringence was checked by using a Berek compensator on thin sections cut normal to the cleavage. The extinction on most of the unbent flakes is parallel, but a few show inclined extinction with a maximum value of 4° with the cleavage. In thin section, this clay mineral is usually colorless. However, some lamellae are faintly colored brown and are slightly pleochroic. The pleochroism shows best in sections normal to (001) and the mineral appears very pale brown when the cleavage is parallel to the vibration direction of the lower nicol, and colorless when at right angles to it. The above listed optical properties are not those of kaolinite as determined by Dick[4] or Larsen,[5] nor do they agree with those of rectorite.[6]

Two samples of this pearly mineral were carefully prepared by the writer from the coarse Ione sandstone forming the banks of the Mokelumne River, one mile west of Lancha Plana, Amador County, California. Microscopic examination showed them to be remarkably pure. Dr. Clarence S. Ross of the U. S. Geological Survey has kindly separated material from the same locality, and through his courtesty the analysis of it by Mr. Fairchild is listed in the accompanying table which records the four independent analyses now available.

[4] Allan B. Dick. Supplementary Notes on Kaolinite, *Mineralog. Mag.*, **XV**, p. 124, 1908.

[5] Larsen, E. S. *Bulletin, U. S. G. S.* **679**, p. 249, 1926.

[6] Larsen, E. S. and Wherry, E. T. Leverrierite from Colorado. *Journal Wash. Acad. Science*, Vol. **7**, p. 215, 1917.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
SiO_2	55.88	54.7	55.0	52.46	55.13	41.02	42.10
Al_2O_3	30.24	31.2	31.1	32.20	31.14	17.99	19.45
Fe_2O_3	0.42	1.2	1.4	1.69		10.50	8.20
FeO	0.16						
MgO			0.41			20.04	17.35
CaO	tr	tr	0.01	0.30			
Na_2O	0.34	x	x	0.25		tr	tr
K_2O	0.42	x	x	0.31		9.35	8.14
H_2O-	0.63	1.8	12.13	13.48	13.73	1.71	5.83
H_2O+	11.72	11.0					
TiO_2	0.50			0.55			
	100.31	99.9	100.05	101.24	100.00	100.61	101.07

x not determined.

1. Ione "anauxite." W. F. Hillebrand analyst. *14th Ann. Rept. U. S. G. S.*, pt. II, 1892, p. 464.
2. Ione "anauxite." Mokelumne River. F. A. Moss, analyst.
3. Ione "anauxite." Mokelumne River. Prof. W. S. Morley, analyst.
4. Ione "anauxite." Mokelumne River. Mr. Fairchild, analyst.
5. Calculated composition to agree with formula $5\ H_2O \cdot 2\ Al_2O_3 \cdot 6\ SiO_2$.
6. Fresh biotite. A. Johnstone. *Quart. Jour. Geol. Society*, Vol. 45, p. 368, 1889.
7. Biotite of composition No. 6, subjected to CO_2 water for one year. A. Johnstone.

These analyses do not differ greatly, and the SiO_2 and Al_2O_3 percentages are very close to that calculated for the formula $5\ H_2O \cdot 2Al_2O_3 \cdot 6\ SiO_2$. Water content is lower, but it is probable the iron, magnesia and alkalies occupy space not yet replaced by hydrogen.

In a preliminary paper read before the Mineralogical Society of America, the name ionite[7] was proposed for this mineral. During the discussion of the paper, Dr. A. F. Rogers suggested that the properties of this hydrous silicate of aluminum were similar to those of beidellite or possibly anauxite. Beidellite is easily eliminated for it differs chemically, possesses slightly lower indices of refraction[8] and greater birefringence. X-ray patterns made on powdered crystal flakes from the Ione formation were compared with those of beidellite from the type locality and are decidedly different. The published data[9] on anauxite do not show very close agreement with the properties of the mineral in the Ione.

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[7] Abstract. *The American Mineralogist*, Vol. 12, p. 78, March, 1927. The designation of a hydrocarbon as ionite by Purnell in 1878 was unknown to the writer when this proposal was made.

Messrs. Clarence S. Ross and William F. Foshag have recently investigated the anauxite from Bilin and were able to furnish material for comparison, and to contribute valuable information concerning it. The optical properties, redetermined by Ross[10] and Foshag are as follows:

Monoclinic six-sided or irregular plates with perfect basal cleavage; extinction parallel to cleavage;

$$\alpha=1.559,\ \beta=1.564\ \gamma=1.565;\ \gamma-\alpha=.006;$$
$$2V=0^\circ-42^\circ;\quad \text{negative};\quad \text{dispersion } \rho>\nu$$

Dr. Foshag's analyses of the anauxite from Bilin indicate an alumina-silica ratio of 1:3, rather than the formula $3\ Al_2O_3\cdot 10\ SiO_2\cdot 8\ H_2O$ as previously given. The optical properties and chemical composition of anauxite as determined by them agree very satisfactorily with those of the mineral in the Ione, and show that the two are probably identical. Dr. P. F. Kerr[11] has compared the X-ray pattern of the Ione mineral with that of anauxite from Bilin, and is of the same opinion.

The field occurrence presented the first suggestion of the origin of the Ione anauxite. In tracing the Ione sandstone eastward towards Valley Springs, a weathered green mineral of a chloritic nature was found to have locally the same mode of occurrence as the anauxite to the west. Its cleavage flakes lie parallel to the bedding, and the space between the sand grains is packed with the

[8] E. S. Larsen and E. T. Wherry. *Jour. Wash. Acad. Science*, Vol. **7**, pp. 207–17, 1917; and Vol. **15**, p. 465, 1925.

C. S. Ross and E. V. Shannon. *Jour. Wash. Acad. Science*, Vol. **15**, p. 467, 1925.

[9] E. Dittler und J. E. Hibsch. Über Anauxit und Cimolit von Bilin. Tschermak's Mineralogische und Petrographische Mitteilungen. Bd. **36**, p. 85 (1923).

[10] See following article in this Journal.

[11] Personal communication.

foliated green mineral. The field relations and a study of the heavy separates show that this bed is a part of the same formation, being deposited during the progressive overlap of the Ione Formation to the east. Thin sections of the sandstone containing chlorite show several grains of feldspar sufficiently fresh to show the twinning lamellae. Feldspar is absent from the sections containing anauxite, which seems to indicate that anauxite develops under conditions that remove the feldspar. The chlorite itself is cut by innumerable small veinlets of anauxite (Fig. 1) which stand out prominently under high magnification, due to a lack of color and to a lower index of refraction, and under crossed nicols show lower birefringence. The chloritic mineral is thus replaced by parallelly oriented anauxite, and grains are present which consist mostly of chlorite with little anauxite, while others are nearly all anauxite with only traces of the original chlorite. The similarity of crystal form and optical orientation suggests that anauxite inherits these from chlorite, and the change in chemical composition causes a loss of color, lower refringence and birefringence and in most cases an increase in the size of the optic angle. Zschimmer[12] in his work on the bleaching of biotite found that as the specific gravity decreased, due mainly to a loss of iron, calcium and potash and corresponding increase in water,

Figure 1

Chlorite, (dark), being replaced by veins of anauxite (white). Ordinary light. X230.

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[12] Eberhard Zschimmer. Die Verwitterungsprodukte des Magnesiaglimmers und der Zusammenhang zwischen chemischer Zusammensetzung und optischem Achsenwinkel der Glimmer. Inaugural Dissertation, Jena, 1898.

the pleochroism disappeared, the index of refraction decreased and the optic axial angle increased. This alteration is not wholly comparable to the development of anauxite, as it takes place under conditions which produce a golden colored mica that is a stable product for those conditions. But, the results are valuable because they show that a considerable change in composition can take place along these lines and the mineral retain its orientation, while certain optical properties vary with the composition. The analyses of the Ione anauxite show only small residual amounts of iron, magnesium, calcium and alkalies and its optical properties are in accordance with what one would expect by analogy with the above.

In preparing samples of the Tertiary stream gravels of the Sierra Nevada for microscopic study by boiling in HCl, the writer found that the chlorite changes to a pearly white mineral, the refractive indices of which are much lower than those of the chlorite before treatment. The chemical composition of this pearly substance was not determined, but it has the characteristic surface appearance of the Ione anauxite and it retains the needles of rutile which occur in the chlorite. Very small needles of rutile can be observed under high magnification in anauxite from the Ione. Some of these are twinned and the occurrence of ring-like forms composed of six individuals in contact at angles of 65° or 54° makes it clear that the inclusions are rutile. This is further substantiated by the analyses of Hillebrand and Fairchild, which show 0.5 and 0.55% TiO_2, respectively. In the other analyses TiO_2 was not determined, and it is included in the Al_2O_3. Teall[13] and others have observed needles of rutile as fine as .001 mm. in clays. This is easily explained if anauxite is a common mineral in clays. The large surface area of its cleavage flakes and its low specific gravity would allow it to act as a raft, floating the inclusions along with the fine sediments to be deposited with them.

It is probable that much of the chlorite, which forms anauxite, was originally biotite. The alteration of biotite to chlorite, which is often accompanied by the development of rutile is widely recognized, and references to it are made in many of the text books of petrography. Near Nevada City, the bed rock of the Manzanita Hydraulic Mine is granodiorite, of which biotite forms a part. In places this is altered to a white compact rock, in which the angular quartz grains occupy the same position as in the fresh rock. White, earthy kaolin probably derived from the feldspars, and plates of anauxite containing rutile inclusions constitute most of the remainder. There is little doubt that the anauxite was derived from the biotite of the granodiorite for its occurrence is identical. The composition of the biotite in the Sierra Nevada granodiorites is known to vary. One of the biotites described[14] contains 36.02% SiO_2 and 18.80% Al_2O_3, and another has 35.75% SiO_2 and 14.70% Al_2O_3. It is conceivable that the original silica-alumina content of the biotite would determine the composition of the anauxite formed from it by removal of the other constituents, provided both silica and alumina remain constant. It might be argued that if such differences existed, these should be shown in the optical properties. With this idea in view, the indices of anauxite from various parts of the Ione were measured. The greatest difference observed in the refractive index of γ was .005 which is too near the limit of accuracy of the immersion method to be certain of the results. The four analyses of anauxite from the Ione show slight disagreement. This might be accounted for by a personal factor. On the other hand, the anauxite in the Ione sands probably was derived from many different biotites and the composition might depend on the original silica-alumina content of the biotites, and the stage to which the replacement had progressed. It is significant that there is less variation in these analyses than in the silica-alumina content of the biotites mentioned.

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[13] J. J. H. Teall. On the Occurrence of Rutile Needles in Clays. *Mineralog. Mag.*, Vol. 7, p. 201, 1887.

An experiment by Johnstone[15] shows how certain constituents in biotite may be removed. Biotite (see Analysis No. 6 in Table) was placed in water containing CO_2 for one year, and the effects noted. The smaller particles lost their pleochroism and much of their color. The resulting product (Analysis No. 7) shows decided loss of magnesium, iron, and potassium which have been removed as carbonates or bicarbonates.

The anauxite of Bilin was formed by the action of CO_2[16] in connection with volcanic activity. The iron, magnesium, calcium and alkalies in the basalt were taken into solution as carbonates and bicarbonates, leaving hydrous aluminum silicates behind. Pseudomorphs of anauxite after augite were formed by this process.

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[14] *Amer. Jour. Sci.*, 4th Ser., Vol. 7, p. 294, 1899.

[15] A. Johnstone. Action of Pure Water and of Water saturated with CO_2 on the minerals of Mica Family. *Quart. Jour. Geol. Soc.*, Vol. 45, p. 367, 1889.

[16] E. Dittler und J. E. Hibsch, *loc. cit.*

Among the rocks of Guinea, Lacroix[17] described a series of mica schists which have been deprived of their alkalies. He gives analyses showing that the removal is progressive, increasing towards the surface. This, he considers, is due to the porosity of the soil rendering easy the penetration of surface waters, along with suitable topographic conditions for the retention of abundant moisture at the surface. But, the heavy forest cover which develops under tropical conditions is even more essential and he cites cases where the leaching is limited to the forested area. This seems logical as alkalies, lime, iron and magnesia are some of the elements taken up by plants, and further in this environment abundant CO_2 would be present to aid in their removal as carbonates and bicarbonates.

The writer considers the anauxite of the Ione formation to have formed by surface weathering under tropical or subtropical climate. The calcium, magnesium, iron and alkalies were removed from biotite as bicarbonates and carbonates. Further evidence for this and a more complete description of the occurrence and importance of this mineral in the Ione formation will be given in another paper.

ACKNOWLEDGMENTS. The writer wishes to express his appreciation to Dr. George D. Louderback for his helpful suggestions during the course of the work and a critical reading of the manuscript. Thanks are due to Dr. Clarence S. Ross of the U. S. Geological Survey for his valuable assistance and the use of his optical and chemical data on anauxite, and to Professor W. J. Mead for his constructive criticisms and the X-ray patterns made at the University of Wisconsin.

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[17] Lacroix, Les Latérites de la Guinée. *Nouvelles Archives du Muséum d'Histoire Naturelle.* Series 5, No. 5, p. 306, 1913.

ANAUXITE, A MINERAL SPECIES, BASED ON MATERIAL FROM BILIN, CZECHOSLOVAKIA[1]

Clarence S. Ross, *U. S. Geological Survey*

and

William F. Foshag, *U. S. National Museum.*

Anauxite was first described from Bilin, Czechoslovakia (Bohemia), by Breithaupt[2] in 1838, and was restudied by Dittler and Hibsch[3] in 1923. Dana[4] classed anauxite as a variety of cimolite but the work of Dittler and Hibsch indicates that it is a distinct mineral species. The examination of a large number of clay specimens by the writers and their comparison with type material from Bilin has shown that anauxite is one of the most widely occurring clay minerals and is especially abundant in many so-called kaolins. This wide occurrence has shown the necessity of a definite knowledge of the chemical and physical properties of anauxite.

The National Museum recently received an ample supply of the altered basalt from Bilin that contains the anauxite. The basalt has been acted upon by thermal, carbonated waters which have produced a porous, light-colored rock. This is now composed of anauxite, cimolite, which appears to be an impure clay aggregate, and various other alteration products. Large phenocrysts that were originally augite and slightly smaller ones of biotite have been altered to anauxite. The best of the altered augite masses were selected and the outer shells of mixed anauxite and "cimolite" were removed under a binocular microscope and then carefully tested for purity in immersion oils under the petrographic microscope. Altered biotite crystals free from residual biotite were selected in the same way. Material of both types were analyzed with the results given below:

The Na_2O, MgO and CaO are present in very minor amounts and are lowest in the most carefully prepared material. It is therefore evident that they are not an essential part of the anauxite molecule, and anauxite is evidently a hydrous, aluminum silicate.

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[1] Published by permission of the Director of the U. S. Geological Survey and the Secretary of the Smithsonian Institution.

[2] Breithaupt, A.; *Jour. pr. Chemie*, vol. **15**, p. 325, 1838.

[3] Dittler, E., and Hibsch, J. E.; *Tsch. Min. Petr. Mitt.*, vol. **36**, p. 85, 1923.

[4] Dana, James D.; The system of mineralogy, 6th Ed., p. 689, 1909.

ANALYSES OF ANAUXITE FROM BILIN, CZECHOSLOVAKIA (BOHEMIA).

Derived from altered augite.[1]

	PER CENT		RATIOS	
SiO_2	54.32	901	901	100×3
Al_2O_3	29.96	293	305	102×1
Fe_2O_3	2.00	12		
MgO	0.14			
CaO	0.32			
Na_2O	0.37			
H_2O-	0.84			
H_2O+	11.80	655	655	109×2
	99.75			

Derived from altered biotite.[2]

	PER CENT		RATIOS	
SiO_2	53.80	892	892	100×3
Al_2O_3	32.48	318	325	109×1
Fe_2O_3	1.12	7		
MgO	0.26			
CaO	0.34			
H_2O-	0.94			
H_2O+	10.98	609	609	102×2
	99.92			

[1] Analysis by W. F. Foshag.

[2] Analysis by F. A. Gonyer.

The anauxite derived from augite gives ratios that are sharply 2:1:3 and this is confirmed by the material secondary to biotite although its ratios are not quite so sharp. It is therefore evident that the correct formula for Bilin anauxite is $2H_2O \cdot Al_2O_3 \cdot 3SiO_2$.

Dittler and Hibsch[5] give the following as the result of two closely agreeing analyses:

ANALYSIS OF BILIN ANAUXITE.

SiO_2	56.56
Al_2O_3	26.09
Fe_2O_3	2.69
MgO	0.11
CaO	0.40
TiO_2	0.38
H_2O	13.58
	99.87

and assign the formula $3Al_2O_3 \cdot 10SiO_2 \cdot 8H_2O$.

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[5] *Op. cit.*

Anauxite has been described as having parallel extinction but careful measurements show that it has a small but distinct angle of extinction.

The physical and optical properties are as follows: Crystal system monoclinic; habit vermicular crystals with perfect basal cleavage; cross section nearly hexagonal in outline. Color white. $\alpha=1.559$, $\beta=1.564$, $\gamma=1.565$, $\gamma-\alpha=.006$. Extinction parallel in one position, slightly inclined in the other, maximum about 1°30′. Orientation as in muscovite $a=Y$, $b=Z$, $c=X$, $2V$ varies from 30° to 42°, mean about 36°. Dispersion $\rho>v$. Cleavage perfect on (001). Luster pearly on (001), subvitrous on prism faces. Dittler and Hibsch give the following physical and optical properties:

Platy grains, silver-white to bluish-white; luster pearly; $\alpha=1.54$, $\gamma=1.55$, $\alpha=c$, $\beta=b$, $\gamma=a$; $2V$ medium large; plane of the optic axis parallel to (010). Acute bisectrix normal to plates (001) H $2\frac{1}{2}$, Sp. Gr. 2.524.

BOOK REVIEWS

ELEMENTS OF OPTICAL MINERALOGY. PART 2. DESCRIPTIONS OF MINERALS. *Second edition.* N. H. Winchell and A. N. Winchell. 424+XVI pages with 333 text figures. Entirely rewritten and much enlarged by A. N. Winchell. John Wiley & Sons, Inc., *New York*, **1927**, Price $5.50.

The student of optical mineralogy will find, upon careful examination, marked changes in this second edition compared with the earlier work published in 1909. By the omission of "Principles and Methods" which has appeared in a separate volume (Part 1. See *Am. Mineral.*, **8**, p. 36) about one hundred additional pages are made available for the descriptions of minerals. This represents an expansion in the descriptive portion of the text of about thirty per cent. The order of presentation, likewise, has been changed from an alphabetical arrangement to the Dana system, which is also essentially the order recommended by the Committee on Nomenclature and Classification of the Mineralogical Society of America.

The text throughout is very liberally illustrated, many of the older cuts have been replaced by better ones and over one hundred additional figures have been added to clarify the descriptive portion. Some idea of the liberal employment of figures may be gained by a casual glance through the sixty-four pages devoted to the discussion of the feldspars. In this portion alone seventy-three figures and diagrams are used to help the student visualize the relationships existing between the optical and chemical properties of the various members of this group.

The book is more than a mere compilation of existing data as in many of the major isomorphous groups the author has attempted, in the light of recent investigations, to offer new interpretations and correlations between composition and optical properties The book is well written, up-to-date, and should be frequently consulted by every advanced student of optical mineralogy.

W. F. H.

THE OPTIC AND MICROSCOPIC CHARACTERS OF ARTIFICIAL MINERALS. A. N. Winchell. *No.* 4, *Science Series, University of Wisconsin Studies*, Madison, Wisconsin. 215+XV pages. 1927.

This is a companion text to the one reviewed above. While the former records the optical properties of all natural minerals, this book contains like information on all artificial, inorganic compounds (referred to as artificial minerals in the text) in so far as these properties have been recorded in the literature. The order of presentation is the same as in the author's "Descriptions of Minerals," namely, the arrangement followed by Dana. Determinative tables for identifying these artificial compounds by optical and other properties, with cross references, constitute the last 35 pages of the book. The tables are based upon the isotropic or anisotropic character of the compound and arranged in order of increasing index of refraction.

By bringing together in a systematic manner into one volume the optical data which formerly were rather widely scattered the author has rendered a service for which petrographers, mineralogists and chemists will be exceedingly thankful.

W. F. H.

THE NATURE, ORIGIN, AND INTERPRETATION OF THE ETCH FIGURES ON CRYSTALS. A. P. Honess. XIII+171 pages, with 16 figures and 79 original photographs of etch figures. John Wiley and Sons, New York, 1927.

This is the first comprehensive treatise on etch figures to be published in the United States, for American mineralogists have generally paid but little attention to this field of investigation. The value of the etch method in the accurate classification of crystals as to symmetry, and especially in connection with X-ray analysis and other methods of study, is well presented.

The history of the development of the etch method is first discussed, and naturally the splendid contributions of Baumhauer and Becke are emphasized. Then follow chapters in which the following are some of the subjects considered: the production and examination of etch figures; the effect of changes in temperature and solvent on the form of the figure; growth, interpretation, and distribution of etch figures; anomalous etch figures; and the importance of the etch figure in isomorphism. A very considerable portion of the text is devoted to a report on the author's study of the etch figures on the following minerals: cuprite, apophyllite, wulfenite, apatite, endlichite, tourmaline, celestite, barite, anglesite, and topaz. The last chapter is devoted to a summary and conclusions. The illustrations are excellent, especially the original photographs of the etch figures observed by the author on the 10 minerals studied by him.

The text is a very creditable and timely contribution to our knowledge of the character and value of etch figures.

Edward H. Kraus

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY.

Academy of Natural Sciences of Philadelphia, February 2, 1928.

A stated meeting of the Philadelphia Mineralogical Society was held on the above date with an attendance of thirty-seven members and eleven visitors. The president, Mr. Clay, presided.

The following were elected to membership: Messrs. J. T. Hendren and H. Stafford; Messrs. Fred Reinitz and Mr. S. B. Gilliard were elected to junior membership.

Mr. Gage exhibited and described certain minerals recently found at Franklin, N. J.

Dr. Paul F. Kerr of Columbia University then addressed the society on "*Mineralogy applied to the study of gems.*" The speaker described the various methods used to distinguish between natural and synthetic sapphires and rubies, between culture pearls and natural pearls; also how to distinguish amber from its various imitations. The talk, which was illustrated by lantern slides was followed by a general discussion.

F. A. Cajori, *Secretary*

THE MINERALOGICAL SOCIETY (ENGLAND)

Mineralogical Society, January 10.—Dr. G. T. Prior, F.R.S., President, in the chair.

Dr. L. J. Spencer: *Potarite, a new mineral discovered by the late Sir John Harrison in British Guiana.* Small nuggets and grains of a brittle white metal have been found very sparingly by diamond-washers in the neighborhood of the Kaieteur Falls on the Potaro River. This mineral, previously erroneously described as "allopalladium," was proved by Harrison to be a compound of palladium and mercury, Pd Hg, with a density (15.0–16.1) considerably higher than that of either of the component metals. There is a crystalline structure which on the surface of one nugget is shown as indistinct cubic octahedra. The original "allopalladium" from the Harz Mts., supposed to be a hexagonal modification of palladium, could not be procured for a re-examination; it is probably the ordinary cubic palladium.

Dr. H. V. Ellsworth: *A simple and accurate constant-volume pycnometer for specific gravity determination.* The pycnometer of 10c.c. capacity is made of silica-glass, thus possessing several advantages over one made of ordinary glass. The stopper is perforated by a capillary and is continued into a graduated side-tube, which dips under water while the apparatus is cooling. The volume of the contained water to the graduations on the side-tube can be readily and accurately determined to 0.0002c.c.

Mr. W. Campbell Smith: *The optical orientation of labradorite from County Down (Ireland), determined by the Fedorov method.* The labradorite from basaltic dikes at St. John's Point, Ardglass, Co. Down, of which the chemical composition and refractive indices were published in 1912 has been studied by the Fedorov method and the optical orientation determined.

Dr. C. E. Tilley demonstrated the inversion of Ca_2SiO_4 in a metamorphic limestone from Larne, Co. Antrim, (Ireland) and Mr. A. F. Hallimond exhibited an electro-magnetic separator for mineral powders.

NEW MINERAL NAMES

Genevite

L. Duparc and M. Gypsin: Sur la genevite, un Nouveau Mineral. (Genevite, a new mineral). *Bull. Soc. Fran. Mineral.*, **50**, 41–46, 1927.

Name: (Derivation not given, perhaps from *Geneva*, Switzerland, residence of L. Duparc).

Chemical Properties: Essentially a silicate of calcium and aluminum. Analysis: SiO_2 37.11, Al_2O_3 16.19, Fe_2O_3 3.05, FeO 2.53, MnO trace, CaO 33.67, MgO 2.17, K_2O 0.66, Na_2O 0.46, H_2O 2.70, Ign. loss 1.01; Sum 99.55. Easily attacked by hot HCl. Fuses at 3 to a gray enamel.

Crystallographic Properties: Tetragonal. Prismatic. Faces $m(110)$. Cleavage (100) poor. The basal section shows two cleavages.

Physical and Optical Properties: Transparent, colorless. Uniaxial. Elongation negative. $n_g=1.707$, $n_p=1.698$.

Occurrence: Found as embedded crystals in a gray limestone interbedded in carbonaceous schists of Paleozoic Age.

Discussion: The mineral shows numerous minute inclusions sometimes arranged along the diagonals of the crystals. (If one considers these inclusions as magnetite and recalculates the analysis upon this basis the mineral falls in a very satisfactory manner into the melilite group with the following mineral composition:[1]

Magnetite 2.7, Soda sarcolite 2.3, Velardenite[2] 20.1, Sarcolite 74.9.

The mineral is then satisfactorily referred to sarcolite. (Abstr.).

W. F. Foshag

Thorotungstite

J. B. Scrivenor and J. C. Shenton: Thorotungstite, a mineral containing tungsten and thorium from the Federated Malay States. *Am. Jour. Sci.*, **13,** 487–490 (1927).

Name: From its main constituents, *thoria* and *tungsten* trioxide and from its resemblance to *tungstite.*

Chemical Properties: A hydrous oxide of tungsten, thorium, cerium and zirconium. Formula $2WO_3 \cdot H_2O + (ThO_2, Ce_2O_3, ZrO_2) \cdot H_2O$. Analysis: (on material pure except for a small amount of silica) WO_3 69.69, Fe_2O_3 1.35, Al_2O_3 4.31, SiO_2 0.48, ThO_2 16.00, rare earths (nearly all cerium) 1.77, ZrO_2 1.96, CaO 1.02, MgO tr., Ign. loss 4.18. Sum 100.76. Attacked by acids. Hot caustic soda partially dissolves it leaving a heavy white flocculent precipitate containing thorium, iron and rare earths.

Crystallographic Properties: Orthorhombic? with pinacoid, prism and dome. Transparent acicular crystals up to 0.8 mm. Cleavage transverse.

Physical and Optical Properties: Color honey yellow. n greater than 1.74. Birefringence high, the interference colors of the crystals lying on the broad face of the fourth order. Optically negative. Sp. Gr. 5.55.

Occurrence: At the Kramat Pulai Ltd. Mine at Pulai Kinta District, Perak, Federated Malay States. It was found as shapeless blocks a few pounds in weight at the base of an alluvial tin bearing deposit overlying granite. Results from the decomposition of scheelite or wolframite (the latter occurs in the granite) and some mineral containing ThO_2 and Ce_2O_3, perhaps monazite and zircon. W. F. F.

Scharizerite

Joseph Schadler: Scharizerite, ein neues Mineral aus der Drachenhöhle bei Mixnitz in Steiermark. (Scharizerite, a new mineral from the Drachenhöhle near Mixnitz, Steiermark). *Anz. Akad. Wiss. Wien.*, **62,** 180 (1925).

Name: In honor of Dr. R. *Scharizer,* Professor of Mineralogy at the University of Graz.

Chemical Properties: A nitrogenous carbon compound. Analysis (by Hans Lieb): C 35, H 4.5, N 8 (average), P tr., Ash 17.Soluble in sodium hydroxide and reprecipitated by hydrochloric acid.

Physical Properties: Massive and black.

Occurrence: Found in fist-size masses and in the brain cavity of fossil bears; also disseminated in the phosphate earth of Drachenhöhle at Mixnitz. Differs from dopplerite and phytokollite in its higher content of nitrogen and in its origin from animal instead of vegetable matter. W. F. F.

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[1] W. T. Schaller, *U. S. Geol. Survey, Bull.* **610,** 109–128 (1916).

[2] Velardenite (gehlenite) is taken as $MgO \cdot 2CaO \cdot 2SiO_2$. See J. B Ferguson and A. F. Buddington: *Am. Jour. Sci.*, **50,** 131–140 (1920).

Shannonite

C. E. Tilley: Unnamed mineral of the olivine group. *Geol. Mag.*, **64**, 143–144 (1927). Original description: Frederick P. Paul. *Tsch. Min. Pet. Mitt.*, **25**, 309–311 (1906).

Name: From the locality, *Shannon* Tier, near Hobart, Tasmania.

Chemical Properties: A silicate of calcium, Ca_2SiO_4 (?). Contains lime but apparently no magnesia. Soluble in dilute hydrochloric acid.

Physical and Optical Properties: Colorless to light gray. Cleavage rectangular, poor. Optically positive. Birefringence $=0.0279, \gamma-\beta=0.0079$. $2V=64°18'$ (Calculated). $2E=125°14', \alpha=1.718, \beta=1.738, \gamma=1.746$. Dispersion $\rho>\nu$.

Discussion: From the analysis of the rock the mineral appears to be essentially Ca_2SiO_4 and to constitute up to 14% of the rock. Tilley believes it to be identical with $\beta-Ca_2SiO_4$ (Day, Shepard and Wright: The lime-silica series of minerals. *Am. Jour. Sci.*, **22**, 265–302, 1906) and names it shannonite. (According to Day, Shepard and Wright $\beta-Ca_2SiO_4$ is unstable below 675° and rapidly inverts to the monoclinic $\gamma-Ca_2SiO_4$ with dusting. The optic axial angle of $\beta-Ca_2SiO_4$ is given as very large. Abstr.). W. F. F.

Rossite

William F. Foshag and Frank L. Hess: Rossite and Metarossite. Two new vanadates from Colorado. *Proc. U. S. Nat. Mus.*, **72**, 1–12 (1927).

Name: In honor of Dr. *C. S. Ross*, of the United States Geological Survey.

Chemical Properties: A hydrous calcium vanadate, $CaO\cdot V_2O_5\cdot 4H_2O$. Analysis: CaO 18, MgO 0.14, V_2O_5 58, H_2O 22.90. Sum 100.64. Soluble in water.

Crystallographic Properties: Triclinic. $x_0=0.4969$, $y_0=0.1624$, $p_0=0.8295$, $\lambda=80°39'$, $\mu=59°31'$, $\nu=85°38'$, $\alpha=98°18'$, $\beta=97°24'$, $\gamma=89°34'$. Habit prismatic. Forms: *c* (001), *b* (010), *a* (100), *m* (110), *y* ($\bar{1}01$).

Physical and Optical Properties: Color yellow. Luster pearly to vitreous. Biaxial. $2V$ large. Plane of the optic axes parallel to the axis *c* with $Z=c$. $\alpha=1.710$, $\beta=1.770$, $\gamma=1.840$. Dispersion strong. Hardness: 2–3;. specific gravity 2.45

Occurrence: Found as small glassy kernels embedded in flaky metarossite at Bull Pen Canyon, San Miguel County, Colorado. W. F. F.

Metarossite

Ibid.

Name: In allusion to its relation to rossite, a partially dehydrated rossite.

Chemical Properties: A hydrous calcium vanadate, $CaO\cdot V_2O_5\cdot 2H_2O$. Analyses CaO 20.04 to 19.60; MgO 0.10 to 0.13; V_2O_5 64.08 to 64.20; H_2O 13.56 to 14.08; insoluble 2.72 to 2.48. Sums 100.50; 100.49. Soluble in water.

Physical and Optical Properties: Color yellow. Luster pearly to dull. Biaxial. $2V$ large. Dispersion strong. $\alpha=1.840$, β and γ higher than 1.85. Soft and friable.

Occurrence: Found as small veinlets in sandstone at Bull Pen Canyon, San Miguel Canyon, Colo., as a dehydration product of rossite. W. F. F.

ERRATA

Vol. 12, p. 251, table, line 2 from bottom, for "1.7474" read "1.7974."